

H/T Scaling of the Magnetoconductance near the Conductor-Insulator Transition in Two Dimensions.

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For an electron density near the $H = 0$ insulator-to-conductor transition, the magnetoconductivity of the low-temperature conducting phase in high-mobility silicon MOSFETs is consistent with the form $\Delta\sigma(H_{||}, T) \equiv \sigma(H_{||}, T) - \sigma(0, T) = f(H_{||}/T)$ for magnetic fields $H_{||}$ applied parallel to the plane of the electron system. This sets a valuable constraint on theory and provides further evidence that the electron spin is central to the anomalous $H = 0$ conducting phase in two dimensions.

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Recent experiments [1,2] have demonstrated that the anomalous conducting phase [3] found in the absence of a magnetic field in two-dimensional electron systems in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) is strongly suppressed by an in-plane magnetic field, $H_{||}$. For electron densities near the $H = 0$ transition (*i.e.* for $\delta n \equiv (n_s - n_c)/n_c \ll 1$, $n_c \sim 10^{11} \text{cm}^{-2}$), an external parallel field as low as $H_{||} \sim 4 \text{ kOe}$ causes an increase in the resistivity, changing the sign of $d\rho(T)/dT$ at low temperatures from positive (metallic) to negative (insulating behavior); the resistivity saturates to a constant value for fields $H_{||}$ above $\sim 20 \text{ kOe}$, indicating that the conducting phase has been entirely quenched. We have shown further [4] that a magnetic field suppresses the conducting phase independently of the angle of application with respect to the 2D electron layer. The total magnetoconductance is the superposition of this term and orbital effects associated with the perpendicular component of the field which give quantum Hall oscillations [5].

The unexpected conducting phase in two dimensions in the absence of a magnetic field has been observed recently for holes in SiGe quantum wells [7] and GaAs/AlGaAs heterostructures [8,9,10]. Although considerably smaller, a negative magnetoconductance (positive magnetoresistance) [10,11] found in these systems has also been attributed to the suppression of the conducting phase.

An in-plane magnetic field affects the spins of the electrons only, and has no effect on their orbital motion. The quenching of the conducting phase by a magnetic field applied parallel to the plane of the electrons thus provides strong indication that the electrons' spins play a central role in the anomalous conducting phase in these two-dimensional systems. We now demonstrate that near the metal-insulator transition, the magnetoconductivity of the $H = 0$ conducting phase in high-mobility dilute silicon MOSFETs scales with H/T , obeying the form

$$\Delta\sigma(H_{||}, T) \equiv \sigma(H_{||}, T) - \sigma(0, T) = f(H_{||}/T). \quad (1)$$

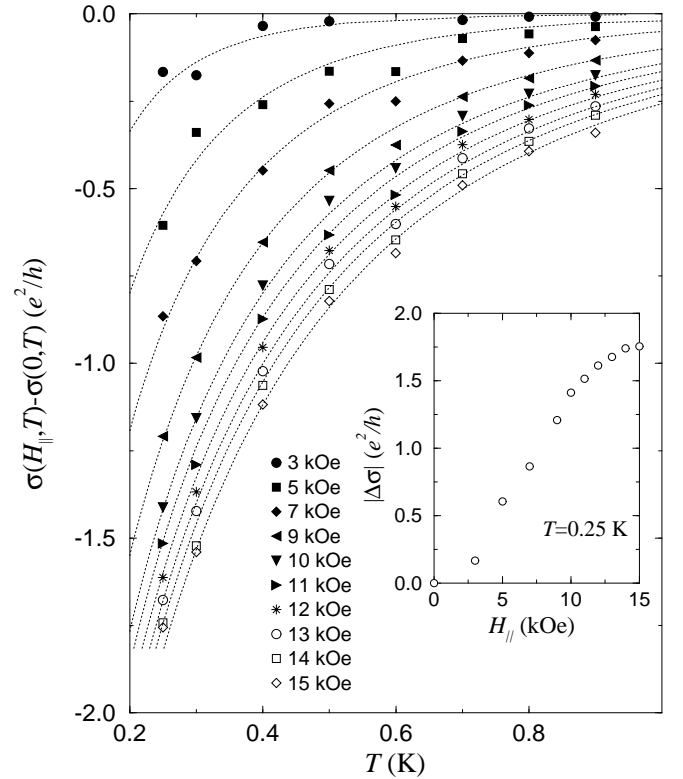


FIG. 1. Magnetoconductivity $\Delta\sigma(H_{||}, T) \equiv \sigma(H_{||}, T) - \sigma(0, T)$ versus temperature T for several magnetic fields $H_{||}$ applied parallel to the plane of the electrons. The sample is in the conducting phase with an electron density $\delta = (n_s - n_c)/n_c = 0.10$. The dotted lines are guides to the eye. The inset shows the absolute value of the magnetoconductivity $|\Delta\sigma(H_{||}, T)|$ versus $H_{||}$ at the lowest measured temperature, $T = 0.25 \text{ K}$. Note the rapid increase of $|\Delta\sigma(H_{||}, T)|$ followed by saturation above $\approx 13 \text{ kOe}$.

The maximum mobility of the sample used in these experiments was $\mu_{T=4.2\text{K}}^{\text{max}} \approx 25,000 \text{ cm}^2/\text{Vs}$. The conductivity was measured in magnetic fields up to 15 kOe applied parallel to the plane of the electrons.

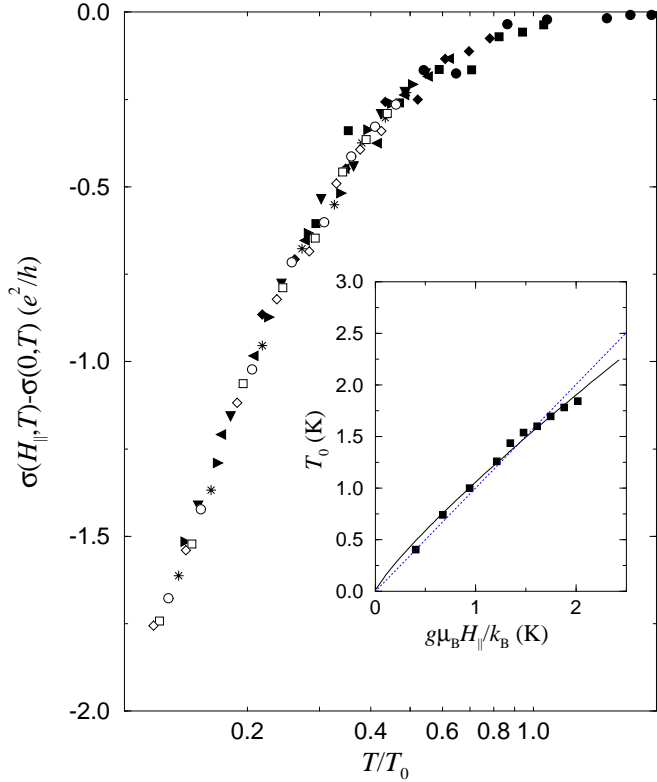


FIG. 2. The magnetoconductance $\Delta\sigma$ as a function of T/T_0 . The inset shows the scaling parameter T_0 plotted as a function of $g\mu_B H_{||}/k_B$. (Symbols for different fields, $H_{||}$, are the same as in Fig. 1). A power-law fit, shown by the solid curve, yields $T_0 \propto H_{||}^\alpha$ with $\alpha = 0.88 \pm 0.03$. The dotted straight line corresponds to $T_0 = g\mu_B H_{||}/k_B$; deviations from straight-line behavior are attributed to saturation at high fields.

Measurements were taken between 0.25 and 0.9 K with the sample immersed in the ^3He - ^4He mixing chamber of a dilution refrigerator. The electron density was set by the gate voltage at $n_s = 9.43 \times 10^{10} \text{cm}^{-2}$, placing the sample on the conducting side and near the conductor-to-insulator transition ($n_c = 8.57 \times 10^{10} \text{cm}^{-2}$). In the absence of a magnetic field, the resistance was 13.9 kOhm at the lowest measured temperature, $T = 0.25$ K.

The magnetoconductivity, $\Delta\sigma(H_{||}, T) = \sigma(H_{||}, T) - \sigma(0, T)$, is shown in Fig. 1 as a function of temperature for various fixed values of parallel magnetic field. The magnetoconductance is negative, its absolute value increasing with applied field and with decreasing temperature. The noise for small $H_{||}$ derives from the subtraction of two large (and comparable) quantities, $\sigma(H_{||}, T)$ and $\sigma(0, T)$. The inset to Fig. 1 shows the absolute value of the magnetoconductivity as a function of $H_{||}$ at a temperature of 0.25 K. The absolute value of magnetoconductance rises rapidly and begins to saturate above ~ 13 kOe, consistent with earlier measurements [1,2]. The data for

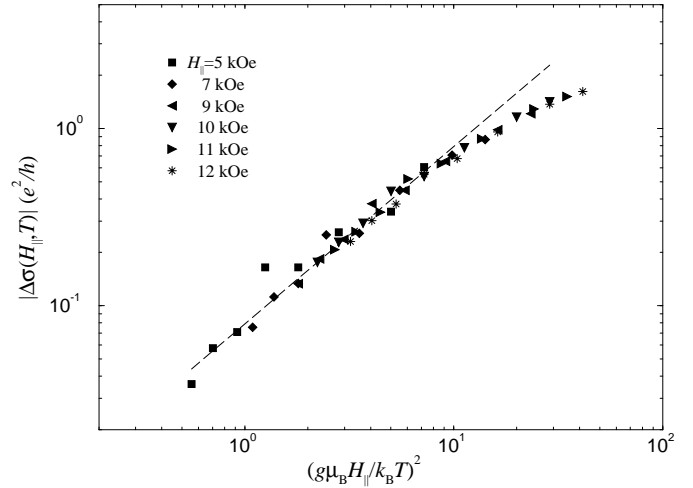


FIG. 3. Magnetoconductance $\Delta\sigma(H_{||}, T)$ versus $g\mu_B H_{||}/k_B T$ on a logarithmic scale for $H_{||} = 5$ to 12 kOe (see text). The dashed line is a fit to Eq. 7 in Ref. [21], $\Delta\sigma(H, T) = -0.084e^2/(\pi h)\gamma_2(\gamma_2 + 1)(g\mu_B H/k_B T)^2$. $\gamma_2 = 1.3$.

$\Delta\sigma$ can be collapsed onto a single curve by applying a different multiplicative factor to the abscissa for each curve, as illustrated in Fig. 2. The scaling parameter T_0 is plotted in the inset as a function of the Zeeman energy, $g\mu_B H_{||}/k_B$ (in Kelvin). Here g is the g -factor (equal to 2 in Si MOSFETs), μ_B is the Bohr magneton, and k_B is the Boltzmann constant. A power-law fit (shown by the solid curve) yields $T_0 \propto H_{||}^\alpha$, with $\alpha = 0.88 \pm 0.03$. We note that H/T scaling of the form Eq. (1) requires that $\alpha = 1$, corresponding to $T_0 = g\mu_B H_{||}/k_B$ (indicated in the inset by the dotted line). We suggest that the deviation of α from unity is associated with the saturation of the magnetoconductance at $H_{||} \gtrsim 13$ kOe shown in the inset to Fig. 1, where one might well expect the scaling to break down. We therefore exclude the data sets at the three largest fields (for which the proximity of the scaling parameter T_0 to saturation is apparent). For in-plane fields in the range $H_{||} = 5 \dots 12$ kOe, the absolute value of magnetoconductance, $|\Delta\sigma(H_{||})|$, is shown as a function of $(g\mu_B H_{||}/k_B T)^2$ in Fig. 3. For this range of magnetic fields and for an electron density fairly close to the critical density, the magnetoconductance scales well with $H_{||}/T$.

Based on quite general arguments, Sachdev [12] showed that the conductivity near a second-order quantum phase transition is a universal function of H/T for a system with conserved total spin. If the magnetoconductance of our silicon MOSFET does indeed scale with H/T (the dotted straight line in the inset to Fig. 2) rather than H/T^α with $\alpha \neq 1$ (the solid curve), this would imply that spin-orbit effects are relatively unimportant near the transition. For a weakly interacting 2D system, Lee and Ramakrishnan [13,14] obtained scaling of the form Eq.(1)

associated with the negative $|S_z| = 1$ triplet channel contribution to the conductance. We note that the scaling reported here for the 2D system in silicon MOSFETs is remarkably similar [15] to the H/T scaling of the magnetoconductance observed by Bogdanovich *et al.* [16] in three-dimensional Si:B near the metal-insulator transition, where it was attributed to the mechanism of Ref. [14]. H/T scaling is also expected within theories that predict various types of superconductivity in a strongly interacting system in two dimensions [17,18,19].

Extending earlier work of Finkel'shtein [20], who showed that a disordered, weakly interacting 2D system can scale toward a metallic phase, Castellani *et al.* [21] have obtained a magnetoconductance $\Delta\sigma(H, T) = -0.084e^2/(\pi h)\gamma_2(\gamma_2 + 1)(g\mu_B H/k_B T)^2$. The coupling constant γ_2 is expected to vary with temperature in the range of validity of the calculation, namely, not too close to the critical density. Our observation of simple H/T scaling for a relative density $\delta_n \ll 1$ implies that γ_2 is at most a weakly temperature-dependent quantity near the transition. The fit to the form suggested in Ref. [21] is shown by the dashed line in Fig. 3, and yields $\gamma_2 \approx 1.3$ ($\gamma_2(\gamma_2 + 1) \approx 3$), corresponding to intermediate coupling strength [22].

To summarize, we have observed scaling of the magnetoconductivity of the form $\Delta\sigma(H_{||}, T) = f(H_{||}/T)$ in the anomalous conducting phase of a two-dimensional system of electrons near the conductor-to-insulator transition. In this, as in other systems where a conducting phase has been observed at low temperatures in the absence of a field, estimates [3,7,8,9,10] indicate that the energy of interactions between carriers is much larger than the Fermi energy in the range of carrier densities where the conducting state exists. The suppression of the conductivity by an in-plane magnetic field is consistent with a decrease of the spin-dependent part of the electron-electron interactions.

Numerous suggestions have been made regarding the nature of the unexpected conducting phase in two dimension in the absence of a field, and a consensus has yet to emerge. Our data provide further evidence that the spins play a central role. Moreover, our finding that the magnetoconductance in the conducting phase near the transition scales with H/T sets a valuable constraint on theory.

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